[Makara Journal of Technology](https://scholarhub.ui.ac.id/mjt)

Volume 26 | Issue 2 Article 5

8-30-2022

Interactive Software-based Modeling for Gait Analysis of Musculoskeletal Structures

Nada Masood Mirza
School of Electric and Electronic Engineering, Universiti Sains Malaysia, Malaysia, 14300, Nibong Tebal, Penang, Malaysia., nada.mirza@student.usm.my

Adnan Ali
2. Information and Technology Center, Al Ain University, Al Ain, UAE, adnan.iqbal@aau.ac.ae

Mohamad Khairi Ishak
School of Electrical and Electronic Engineering, University Sains Malaysia, Nibong Tebal, 14300 Penang, Malaysia, khairiishak@usm.my

Recommended Citation

Mirza, Nada Masood; Ali, Adnan; and Ishak, Mohamad Khairi (2022) "Interactive Software-based Modeling for Gait Analysis of Musculoskeletal Structures," *Makara Journal of Technology*: Vol. 26: Iss. 2, Article 5.
DOI: 10.7454/mst.v26i2.1542
Available at: https://scholarhub.ui.ac.id/mjt/vol26/iss2/5

Makara J. Technol. 26/2 (2022), 73–80
doi: 10.7454/mst.v26i2.1542

Interactive Software-based Modeling for Gait Analysis of Musculoskeletal Structures

Nada Masood Mirza[1], Adnan Ali[2], and Mohamad Khairi Ishak[1*]

1. School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Pulau Pinang 14300, Malaysia
2. Information and Technology Center, Al Ain University, Abu Dhabi 112612, United Arab Emirates

[*]*E-mail: khairiishak@usm.my*

Abstract

Software for interactive musculoskeletal modeling applies diverse scientific and technological concepts to stimulate the movement of musculoskeletal figures. Several tools are available for biomechanical analysis in studying motion and capturing the musculoskeletal representation data to facilitate further evaluation for muscle activation. Musculoskeletal software, such as the OpenSim model, animates, and measures in 3D the structural movement of bones, muscles, joints, ligaments, and such structures in the human body. Users apply graphical interfaces to manipulate the movement science for fast and accurate analysis. OpenSim simulation software features a user-friendly interface to allow the proper clinical application in biomechanics and rehabilitation research. The exploitation of the potential features and outputs is significant to optimize electromyography technology for musculoskeletal simulation. Emphasis on testing fundamental hypotheses with posture experimentation and simulation encourages the adoption of OpenSim in various biomechanical models.

Abstrak

Pemodelan Interaktif berbasis Perangkat Lunak untuk Analisis Cara Berjalan pada Struktur *Musculoskeletal*. Perangkat lunak untuk pemodelan *muskuloskeletal* interaktif menerapkan beragam konsep ilmiah dan teknologi untuk merangsang pergerakan struktur muskuloskeletal. Beberapa metode tersedia untuk melakukan analisis biomekanis dalam mempelajari gerakan dan menangkap data representasi muskuloskeletal untuk memfasilitasi evaluasi lebih lanjut untuk aktivasi otot. Perangkat lunak muskuloskeletal, seperti model OpenSim, menganimasikan, dan mengukur gerakan struktural tulang, otot, sendi, ligamen, dan struktur seperti itu dalam tubuh manusia, dengan representasi 3D. Pengguna menerapkan antarmuka grafis untuk memanipulasi ilmu gerakan untuk analisis yang cepat dan akurat. Perangkat lunak simulasi OpenSim memiliki antarmuka yang ramah pengguna untuk memungkinkan aplikasi klinis yang tepat dalam penelitian biomekanik dan rehabilitasi. Eksploitasi fitur dan output yang potensial sangat penting untuk mengoptimalkan teknologi elektromiografi untuk simulasi muskuloskeletal. Penekanan pada pengujian hipotesis mendasar dengan eksperimen dan simulasi postur mendorong adopsi OpenSim dalam berbagai model biomekanik.

Keywords : *computed muscle control, interactive musculoskeletal modeling, musculoskeletal simulation, neuromusculoskeletal biomechanics, OpenSim*

1. Introduction

Studying and analyzing the way humans walk has been a considerable interest from the early historical times. Studies were mostly conducted for intellectual reasons in the beginning but later on became a primary aspect of rehabilitation techniques for disabled humans in the middle ages. Gait analysis is currently conducted for research and applied clinical use, but both studies are interconnected and co-dependent on each other. Knowing the exact and accurate parameters of a normal gait is crucial to analyzing the one with defects.

Numerous studies, which include Anderson and Pandy [1], Neptune *et al*., [2], Arnold *et al*. [3], Kimmel and Schwartz [4], and Liu *et al*., [5], have developed successful ways to examine and populate the results of unimpaired gait muscular and joint moments. Musculoskeletal modeling is performed for effective gait analysis and comparison. This modeling is specifically conducted in the field of biomechanics. Efficient models are also used to investigate the unmeasurable biomedical variables. They are also used to replace the actual dreadful or non-ethical experiments. Few applications of musculoskeletal models include deciding on the surgical process through simulation to measure the load on joints and identify useful patterns to avoid the risk of sports activity-induced injuries [6–9].

Musculoskeletal models can also be used to give an overview and prediction of body movements during vehicle collisions or exhaustive sports [10, 11]. Simulations can also be utilized to identify, test, and predict the results of "what if" studies [9, 12].

This paper is organized as follows. Sections 2 and 3 describe a complete theory related to a musculoskeletal model designed using various simulation applications, and their comprehensive comparisons further through data analysis models are examined. Sections 4 and 5 are related to the discussion regarding the implementation of a few of these models and the comparison of simulated results with the practical ones, respectively.

2. Materials and Methods

Gait data analysis. The history of the gait analysis goes back to 1994 when [13] proposed one of the first-ever holds to recognize the gait of human beings. The analysis was based on a substantially small database. The HumanID program was later developed by the Defense Advanced Research Projects Agency [14]. The database, which was available for the public free of cost, was established by this program.

Clinical gait analysis (CGA) is conducted to analyze the reasons behind the way patients walk. Several factors play crucial roles in developing one's specific way of walking. CGA can provide information on the following four key data types: kinematics, electromyography data, kinetics, and spatiotemporal [15].

Normal gait patterns can be altered due to an accident, injury, or pain. If that alteration is left unchecked, then it can also lead to various health issues. These issues can be related to mental health problems or cardiovascular health and musculoskeletal issues. Some of the diseases that can lead to altered normal gait are cerebral palsy, osteoarthritis, rheumatoid arthritis, stroke, head injury, spinal cord injury, and Parkinson's disease [16]. Table 1 shows a summary of a few gait abnormalities and their possible reasons.

The overall progress of a patient undergoing treatment of one of the mentioned diseases can also be conducted using the regular validation of one's gait analysis. The results easily help identify the domain under which the patient is responding to the treatment method and that under no change for a long time; thus, mode of treatment can be changed if possible [16].

In the early days, gait recognition was performed using video-based systems. These systems were based on two types of methodologies: model-free and model-based. In the model-free method, one human body was modeled and features were extracted from it. For example, Chundo *et al.* [17] developed the leg model using the pendulum. Cadence and stride were used by BenAbdulkader [18] in 2002 for gait recognition. Similarly, 3D temporal models were introduced by Urtasun and Fua [19].

Model-based approaches were used by several, and human gait was represented as a whole without the knowledge of the underlying structure of the human body. Gait Energy Image and Gait History Image were introduced by Han and Bhanu [20] and Liu and Zhang [21], respectively.

Various sensors have recently been used to study the gait as shown in Table 2. These sensors include floor sensors, accelerometers, and radars. Moreover, these sensors are used in accordance with their types. For example, floor sensors are utilized inside the ground or floor to detect the foot movement of any human being walking on it. Similarly, the wearable sensors are placed on different parts of the body, such as the arms, legs, and hips, and other parts are related to the desired data set of body movements [22]. The overall system of gait recognition is given in Figure 1.

Table 1. Common Gait Abnormalities and Their Possible Causes [16]

Gait abnormalities	Causes
Foot slap at heel contact	Less dorsiflexor activity at heel contact
Forefoot or flatfoot initial contact	Short step length Structural limitation
Short step	Weak push-off Weak hip flexors
Stiff legged weight bearing	Excessive normal extensor activity
Weak push-off	Excessive hip flexor activity during the early swing or late push-off
Hip hiking in swing	Intense extensor synergy

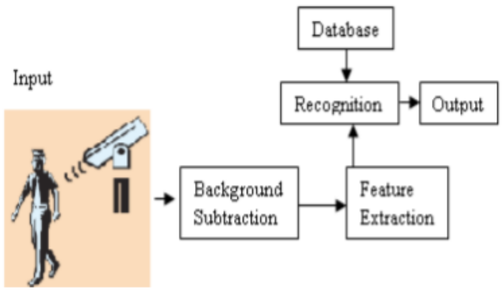

Figure 1. Gait Analysis Block Diagram [22]

Table 2. Milestones Related to the Gait Analysis [23]

Work	Year	Description
[13]	1994	First system to recognize the gait
[17]	1997	First gait recognition system based on models
[24]	2000	First gait recognition system with floor sensors
[25]	2005	First gait recognition system with continuous-wave radar
[26]	2005	First gait recognition system with accelerometer
[20]	2006	First gait recognition system without model

3. Musculoskeletal Models

The study of neuromuscular coordination allows the use of musculoskeletal models to simulate the science of movement for effective injury/disease treatment and performance enhancement. The musculoskeletal model comprises bones, muscles, tendons, and ligaments, along with wrapping objects for completeness [27]. The correct activation of each muscle group induces joint movements accordingly. Biomechanical modeling approaches allow the analysis of athletic performance and estimation of musculoskeletal loads through computer simulation of the simulation model. Observation alone is unrealistic; thus, various software for building, validating, and studying movement science are available. Models are used in biomechanics as a prototype of the physical structures of the system and the functional interactions under investigation. Multiple software allows engineers to design physical models similar to the embodiment of the actual object. Hence, engineering realizes the achievement of various biomechanical investigations from an individual, institutional, and communal viewpoint. OpenSim, AnyBody, Software for Interactive Musculoskeletal Modeling (SIMM), Musculoskeletal Modeling Software (MSMS), and Biomechanics of the body (BoB) are among the software applied in musculoskeletal modeling. Innovative techniques include Motion Capture Importer, Gait Reporting, Scripting, Model Scaling, Muscle Wrapping, Live Plots, Bone Deformations, Video import/expert, Skins, and GUI. [28]. OpenSim compatibility is popular in studying human movement. OpenSim is based on Java and C++ [29]. Such models allow users to simulate the human physical structure and analyze motion when standing, walking, jumping, sitting, throwing, waving, running, swimming, and lifting weights. Table 3 depicts a comparison of the main features of different musculoskeletal modeling software.

Table 3. Comparison of the Main Features of Different Musculoskeletal Modeling Software [28]

Software	Features
OpenSim	Free license
	No native Simulink exports
	Inverse kinematics utility
	Enables dynamic simulations
	Can develop muscle-driven forward dynamic using recorded data
AnyBody	Commercial license
	No native Simulink exports
	Inverse dynamics utility
	Friction forces simulation
	Enables implant modeling
SIMM	Commercial license
	No native Simulink exports
	Inverse kinematics utility
	Allows real-time viewing
	Enables bone deformation modeling
MSMS	Free license
	Directly allows native Simulink export
	Allows real-time data capturing and viewing
	Customizable OpenSim importing tool for all solid works, muscle fiber type, apportion method, recruitment type, and maximum recruitment excitation value
Life MOD	Commercial license
	Easy to model the human skeletal model
	Lack of control algorithms
	Less accurate

While recognizing the existence of other neuromusculoskeletal biomechanics software, such as BoB and AnyBody, this article reviews OpenSim as a leading open-source software system for human movement analysis. OpenSim applies the science of robotics, mechanics, neuroscience, and biology to develop musculoskeletal dynamics accurately for in-depth motion assessment. The paper argues that the movement simulation model obtained from OpenSim offers advanced dynamic features, such as computed muscle control (CMC) and residual reduction for precise motion analysis. Computational scientists rely on continuous reproduction and extension of human movement simulation tools to design cutting-edge software tools.

4. OpenSim Platform

OpenSim is a free and anonymously accessible computational biology software with features that study biomechanical structures and control neuromuscular motion by determining the movement force and torque for strategic rehabilitation. The OpenSim musculoskeletal model has rigid body segments with joint connections. Muscles are designed to span joint movements by generating forces and motions. Upon the creation of the musculoskeletal model, software users can actively analyze the impact of muscle–tendon attributes, joint kinematics, and musculoskeletal geometry based on the generated forces and moments [31]. OpenSim also enables the creation of custom studies whose framework is added to a range of dynamic simulation models to enhance the study and quantification of movement in animals and humans. The software allows access to existing models that users can alter to meet posture and motion expectations through inverse and forward dynamics and kinematics. A simple model of the human body is presented in Figure 2 [29].

Further study of the experimental data provides solutions for underlying dynamic problems. Through musculoskeletal analysis, the eyes of orthopedic patients promises results following creative surgery using assistive devices [32]. The outcomes of using OpenSim motion analysis include optimized biomechanical observations for safe movement and reduced injury occurrences. OpenSim analyzes how the neural, skeletal, and muscular systems interact to produce movement when performing fundamental tasks. The software calculates variables, such as muscle force, tendon recoils, and stretches, which are challenging to determine experimentally. OpenSim also allows the prediction of novel movements from human kinematic adaptations and other motor control models. Post-surgical musculoskeletal dynamic transformations are possible with OpenSim following a human–tool interaction. These transformations introduce the invention of implantable mechanical devices to improve human physical structure movements, such as correcting paralysis. Evaluating and biomechanically analyzing step-up activities by doctors using OpenSim improves understanding of knee implant motions. Simulating cervical spine injuries, spinal cord injuries, and other locomotor abilities predicts the success of surgical interventions.

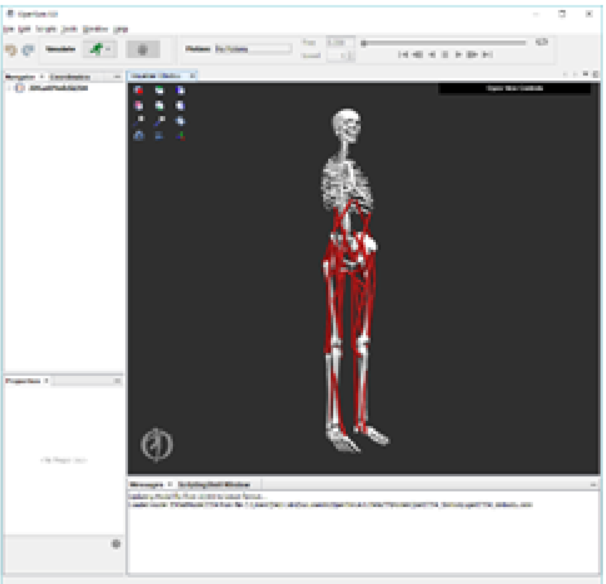

Figure 2. OpenSim GUI

OpenSim is used in diverse fields that aim to understand the reaction of human and animal physical structure to system dynamics. Gaining insights into the functional roles of specific muscles in the human gait is possible with OpenSim, thereby allowing efficient treatment of gait disorders emanating from stroke and cerebral palsy. Access to OpenSim provides a wide scope of design and implementation studies into human and animal models. Comparative biologists use OpenSim to expound on the interaction of animal forms and functions, while engineers can formulate and analyze assistive devices with the simulation model as shown in Table 3. For instance, OpenSim has been used to study animal locomotion by representing compliant tendons with a CMC tool [33]. Simulating and experimenting with reflexes and spinal circuits allows surgeons to conduct corrective surgery successfully and prevent injuries and movement disorders. Electromyography (EMG) in OpenSim facilitates the study of muscle activation patterns, wherein sports performance trainers can evaluate athletic performance using tools, such as force plates and videography. Visualization of this biomechanical data increases the applicability of OpenSim in generating reliable feedback for athletes to improve performance effectively and efficiently.

OpenSim thematic analysis can understand other biological systems, such as cardiovascular, cellular, molecular, and neural functions. The tool simplifies data familiarization, thereby saving time and creating a flexible approach for obtaining desired outcomes. The application of OpenSim in musculoskeletal modeling is helping the healthcare industry in advancing patient care with a personalized touch while lowering the treatment cost. Doctors can predict the most effective treatment for surgical and rehabilitation approaches surrounding neurological and musculoskeletal impairments. The muscle-actuation ability of musculoskeletal modeling improves the interaction of the cause and effect of the particular variables. However, OpenSim leaves room for erroneous approximations and estimations because the musculoskeletal modeling process discounts some muscular properties, such as contraction velocity and history, fiber/muscle length, tendon elasticity and stiffness, and pennation angle [34]. Although OpenSim is a reasonable tool for motion analysis, basic assumptions will impact the musculoskeletal modeling outcomes. Moreover, the data input from the OpenSim motion capture system should be converted to.trc format, yet no software is readily available.

Table 4. Previously Reported Musculoskeletal Models. Muscle–tendon Units [28]

Authors	Source	Software	Year	MTU	Main features
Cardona and Garcia [28]	21 cadavers	MSMS	2019	44/10	Similar to other models, it omits some lower limb muscles. However, the muscles have no significant impact on the outcomes because they make a small contribution to the moment generated at the joints.
Lai K. [35]	21 cadavers, 24adults same as Rajagopal's Model	OpenSim	2017	40/0	Obtaining a similar model in Simulink is difficult. Moreover, the inability to integrate with simulations of exoskeleton control systems, the model cannot define muscle fiber type, maximum recruitment excitation value, apportion method, and recruitment type.
Rajagopal *et al*. [36]	21 cadavers, 24 adults	OpenSim	2016	40/0	It is impossible to get a similar model in Simulink. Also does not allow the definition of muscle fiber type, recruitment type, apportion method, and the maximum recruitment excitation value. The model cannot be integrated with exoskeleton control system simulations.
Carbone *et al*. [37]	Single cadaver	AnyBody	2015	55/12	The model is not ideal to scale a variety of subjects because it only reflects a single cadaver subject.
Chauhan R. [27]	Arnold's model	MSMS	2013	36/0	This model does not allow the generation of the correct forces in muscles, such as gastrocnemius, iliacus, and psoas, because it omits wrapping objects.
Modenese *et al*. [38]	Single cadaver	SIMM /OpenSim	2011	38/14	While it is validated using hip contact forces and EMG, this model may be unreliable if the single subject does not accurately represent other subjects.
Horsman K. [39]	Single cadaver	SIMM /OpenSim	2007	38/14	The musculotendon parameters depend on a single cadaver; however, determining how the single subject represents the others is difficult.

The main limitation of the study of human movements lies in the existence of different simulation and optimization software tools with limited supportive data. Multiple open-source software packages enable scientists and surgeons to collect and analyze experimental movement data using modeling and simulation tools. Despite such resources, human physical movement depends on musculoskeletal dynamics, such as neural control signals and joint loads, which are difficult to compute. Innovative approaches have diversified the application of simulation software beyond muscular and skeletal systems. Multiple musculoskeletal modeling software are available. Thus, users should assess the underlying problem, cause, and effect to determine the most appropriate tool.

5. Implementations Models

During the past times, many research groups compared the results of simulated models and the signals received using sensors implanted in human beings. In 2011, I Modenese [38] initially compared the simulation of the human lower limb with the values read using EMG by [40] and muscle force prediction during the stair climbing by [41]. Comparison of simulated results with the EMG signals is shown in Figure 3. Gray shaded areas represent the EMG results, whereas thin black lines are the muscle force from the gait trial.

OpenSim simulator was later used in 2016 by Apoorva Rajagopal *et al.* [36] to compare the values of actual moments with the simulation ones. The CMC algorithm was adopted during this study. In Figure 4, the simulation results obtained from CMC in OpenSim are compared with the values acquired from the planted EMG sensors on the body of the subjects.

In 2017, research was conducted by Adrian KM Lai *et al.* [35] regarding the prediction of muscle-driven forces by the joints using simulations. The results were compared with EMG signals received by the subjects during walking, pedaling, or running. These results were sufficiently close to predicting all kinds of forces applied by leg joints during the studied movements. However, the results were also simultaneously far from the EMG signal values due to some flaws in the model. Two models, namely intermediate and refined, were used during this research. Figure 5 depicts the comparison between EMG signals and values attained from the simulation of both models.

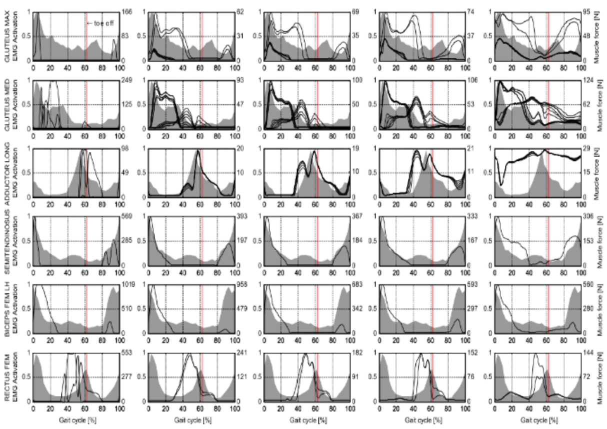

Figure 3. EMG Signal and Simulation Results in Comparison [38]

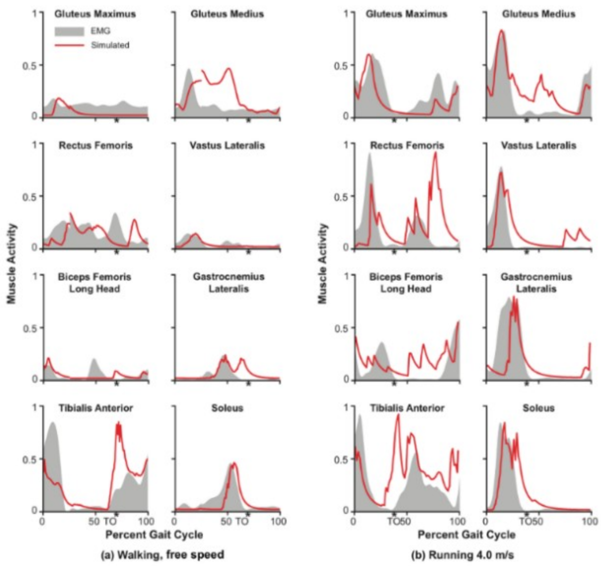

Figure 4. EMG Signal and Simulation Comparison [36]

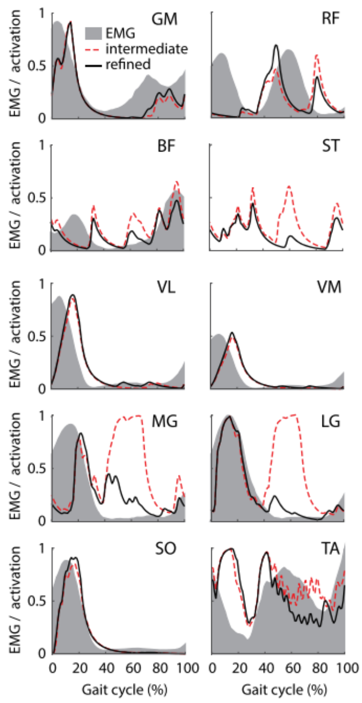

Figure 5. Muscular Movement Comparison with the Simulation Results [35]

Figure 5 presents the following muscles under study: gluteus maximus(GM), rectus femoris (RF), biceps femoris long head (BF), semitendinosus (ST), vastus lateralis (VL), vastus medius (VM), medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SO), and tibialis anterior (TA).

6. Conclusion and Recommendations

According to the results of the comparative study, various simulation software tools are being developed and used by research teams to examine the biomechanics of the human body. These investigations aid in the comprehension of dynamic muscle function. The data obtained from the simulation are usually compared to electromyographic signals for validation. These musculoskeletal models can be beneficial in the prediction and treatment of any joint-related diseases according to the relative analysis of these studies. In addition, OpenSim is the ideal simulation software for any academic project because it is freely accessible and offers a large pool of users and studies for additional knowledge support. However, BoB is the direct model to conduct rapid and accurate biomechanical tutorials and applications. AnyBody is adjustable to the demands of applicants to produce detailed simulations considering the focus investigation for a sophisticated option. Nevertheless, musculoskeletal modeling is a current trend in the health sector, offering promising results in treating movement disorders, such as weak muscles, deformed bones, abnormal muscle excitations, and other movement dynamics that require 3D observation for effective understanding. OpenSim application has facilitated investigations surrounding athletic performance evaluation, musculoskeletal surgical procedures, neuroprosthesis, musculoskeletal loads, and neuromuscular coordination.

However, some of the muscular properties, such as contraction velocity, muscle length, contraction history, fiber length, stiffness, tendon elasticity, and pennation angle, cannot be simulated properly. Therefore, basic assumptions are considered to complete the study. Hence, the dream of modeling and simulation methods for telemedicine must be precisely modified and realized. As always, the real and simulated values are occasionally significantly different. Meanwhile, OpenSim can be considered a major accomplishment in developing instruments that are as reliable as possible for professionals in medicine, rehabilitation scientists, and doctors to predict and treat joint conditions.

References

[1] F.C. Anderson, M.G. Pandy, Gait Posture 17/2 (2003) 159.
[2] R.R. Neptune, F.E. Zajac, S.A. Kautz, J. Biomech. 37/6 (2004) 817.
[3] S. Arnold, F.C. Anderson, M.G. Pandy, S.L. Delp, J. Biomech. 38/11 (2005) 2181.
[4] S.A. Kimmel, M.H. Schwartz, Gait Posture 23/2 (2006) 211.
[5] M.Q. Liu, F.C. Anderson, M.G. Pandy, S.L. Delp, J. Biomech. 39/14 (2006) 2623.
[6] K.M. Steele, A. Seth, J.L. Hicks, M.S. Schwartz, S.L. Delp, J. Biomech. 43/11 (2010) 2099.
[7] S.J. Piazza, S.L. Delp, J. Biomech. Eng. 123/6 (2001) 599.
[8] S.G. McLean, A. Su, A.J.V.D. Bogert, J. Biomech. Eng. 125/6 (2003) 864.
[9] J.A. Reinbolt, A. Seth, S.L. Delp, Procedia IUTAM 2 (2011) 186.
[10] J. Rasmussen, S. Tørholm, M. de Zee, Int. J. Ind. Ergon. 39/1 (2009) 52.
[11] J.Z. Wu, S.S. Chiou, C.S. Pan, Ann. Biomed. Eng. 37/6 (2009) 1177.
[12] J.P. Paul, Ann. Rheum. Dis. 48/3 (1989) 179.
[13] S.A. Niyogi, E.H. Adelson, Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. 1 (1994) 469.
[14] S. Sarkar, P.J.J. Phillips, Z. Liu, I.R.I.R. Vega, P. Grother, K.W.K.W. Bowyer, IEEE Trans. Pattern Anal. Mach. Intell. 27/2 (2005) 162.
[15] S. Armand, G. Decoulon, A.B. Mazure, Efort Open Rev. 1/12 (2016) 448.
[16] T.L. Switaj, F.G. O'Connor (Ed.), The Sports Medicine Resource Manual, 1st ed., Elsevier, Amsterdam, 2008, p.536.
[17] D. Cunado, M.S. Nixon, J.N. Carter, Lecture Notes Comput. Sci. 1206 (1997) 93.
[18] C. BenAbdelkader, R. Cutler, L. Davis, Proceedings 5th IEEE International Conference on Automatic Face Gesture Recognition, Washington, DC, USA, 2002, p.372.
[19] R. Urtasun, P. Fua, Proceedings-Sixth IEEE International Conference on Automatic Face and Gesture Recognition, Seoul, Korea, 2004, p.17.
[20] J. Han, B. Bhanu, IEEE Trans. Pattern Anal. Mach. Intell. 28/2 (2006) 316.
[21] J. Liu, N. Zheng, Proceedings of the 2007 IEEE International Conference on Multimedia and Expo, Beijing, China, 2007, p.663.
[22] A. Hayder, J. Dargham, A. Chekima, G.M. Ervin, Int. J. Comput. Electron. Eng. 3/4 (2011) 477.
[23] C. Wan, L. Wang, V.V Phoha, ACM Comput. Surv. 51/5 (2018) 1.
[24] K. Nakajima, Y. Mizukami, K. Tanaka, T. Tamura, IEEE Trans. Biomed. Eng. 47/11 (2000) 1534.
[25] M. Otero, Proceedings of SPIE-The International Society for Optical Engineering, Florida, United States, 2005, p.538.
[26] H. Ailisto, M. Lindholm, J. Mäntyjärvi, E. Vildjiounaite, S.-M. Mäkelä, Proceedings of SPIE-The International Society for Optical Engineering, Florida, United States, 2005, p.7.

[27] R. Chauhan, J. Vyas, Int. J. Sci. Res. Dev. 1/2 (2013) 2321.
[28] M. Cardona, C.E.G. Cena, IEEE Access 7 (2019) 92709.
[29] J. Yu, S. Zhang, A. Wang, W. Li, Int. Conf. Adv. Mechatron. Syst. (2020) 278.
[30] M. Asif, *et al*., IEEE Access 9 (2021) 85956.
[31] A. Seth, M. Sherman, J.A. Reinbolt, S.L. Delp, Procedia IUTAM 2 (2011) 212.
[32] J.W. Holmes, Am. J. Physiol. Adv. Physiol. Educ. 30/2 (2006) 67.
[33] A. Seth, *et al*., PLoS Comput. Biol. 14/7 (2018) e1006223.
[34] J.B. Langholz, G. Westman, M. Karlsteen, Procedia Eng. 147 (2016) 281.
[35] K.M. Lai, A.S. Arnold, J.M. Wakeling, Ann. Biomed. Eng. 45/12 (2017) 2762.
[36] A. Rajagopal, C.L. Dembia, M.S. DeMers, D.D. Delp, J.L. Hicks, S.L. Delp, IEEE Trans. Biomed. Eng. 63/10 (2016) 2068.
[37] V. Carbone, *et al*., J. Biomech. 48/5 (2015) 734.
[38] L. Modenese, A.T.M. Phillips, A.M.J. Bull, J. Biomech. 44/12 (2011) 2185.
[39] M.D.K. Horsman (Ed.), The Twente Lower Extremity Model, Twente Medical Systems International, Netherlands, 2007, p.159.
[40] M.E. Wootten, M.P. Kadaba, G.V.B. Cochran, J. Orthop. Res. 8/2 (1990) 259.
[41] J. McFadyen, D.A. Winter, J. Biomech. 21/9 (1988) 733.